

# A star disrupted by a stellar black hole as the origin of the cloud falling towards the Galactic center

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## ABSTRACT

We propose that the cloud of gas moving on a highly eccentric orbit around the central black hole in our Galaxy, reported by Gillessen et al. , is produced by a wind from photoevaporating debris orbiting around a star with a small circumstellar disk. The disk is tidally truncated to less than 1AU at the peribothron passage, and a cloud like the observed one is recreated by the wind at every orbit. The star-disk system, which may have been producing the cloud for hundreds of orbits in the past, is proposed to have formed when the star flew by a stellar black hole and was tidally disrupted and deflected to its present orbit. Encounters of low-mass stars with stellar black holes are likely to occur at the location of this cloud, because of the high density of stellar black holes expected to have migrated to the Galactic center by mass segregation. The rate of these encounters at a small enough impact parameter to disrupt the star may reasonably be  $\sim 10^{-6}$  per year. The flyby should have spun up the star and pulled out a substantial fraction of its mass as tidal debris, part of which fell back onto the star and created a small disk. Since then, the disk may have expanded by absorbing angular momentum from the star up to the tidal truncation radius. Thereafter, the strong tidal perturbation of the outer disk edge at every peribothron may create gas streams moving out to larger radius that can photoevaporate and generate the wind that produces the cloud at every orbit. The model predicts that when the cloud is disrupted at the next peribothron passage in 2013, a smaller unresolved cloud will follow the star on the same orbit that will gradually grow. An increased infrared luminosity from the disk may also become detectable during the peribothron passage.

*Subject headings:* galactic center — black holes — stellar structure — stellar winds

## 1. Introduction

Drawing on the vast technological advance in adaptive optics, infrared detectors and X-ray telescopes, observations over the last two decades have revolutionized our knowledge of the Galactic

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Center region. It is now beyond reasonable doubt that a black hole of mass  $4 \times 10^6 M_\odot$  is present at the center of the Milky Way surrounded by a stellar cusp with a total mass in stars of  $\sim 10^6 M_\odot$  within the central parsec (for a review, see Genzel et al. 2010). Several massive young stars are present in the central 0.1pc with well determined orbits, many of which are part of a disk structure and were born in a starburst  $\sim 6$  Myr ago. Hot gas is also present throughout this region, believed to originate from the stellar winds of these massive stars.

A mysterious cloud of gas was also reported recently by Gillessen et al. (2012), moving along a Keplerian orbit. The cloud emits  $5 L_\odot$  of continuum infrared light interpreted as dust emission at a temperature of 550 K, and hydrogen and helium recombination lines consistent with a photoionized cloud with a gas temperature of  $10^4$  K. The cloud is being rapidly disrupted as shown by a clear velocity gradient along its resolved long axis of  $\sim 100$  AU, which is consistent with the tide along its highly eccentric orbit: the cloud has fallen from an apobothron at 8000 AU and will pass through peribothron at 250 AU in summer 2013.

The origin of this cloud is a most intriguing question. Three possibilities have been proposed so far. In the first one, the cloud is isolated and diffuse and was formed by the collision of stellar winds from massive stars (Burkert et al. 2012). Stars near the inner edge of the disk at a distance  $r = 8000$  AU from the black hole, where the circular velocity is  $v_c \simeq 700 \text{ km s}^{-1}$ , may emit winds at velocities close to  $v_c$  and leave the ejected material at low velocity where it might cool after being shocked to high density in a collision and fall on the observed highly eccentric orbit. This model faces several difficulties: it is not clear why only one prominent cloud should be produced at low velocity when there are many stellar winds, without a clear candidate among them that might have produced the cloud near the observed apocenter. The cloud needs to cool down and be confined by the pressure of the external hot medium since its self-gravity is completely negligible, so it is hard to explain why the cloud avoided fragmenting as it moved through the hot medium from its apocenter. In addition, there is no explanation for how the observed dust can form in a cloud at  $10^4$  K that has cooled from gas shocked to millions of degrees after being ejected in a wind from a hot star, without any previously existing cold gas to mix with.

A second possibility might be that an evolved star is losing mass that is producing the cloud at every orbit, which might be observed as a planetary nebula were it not tidally removed at every peribothron passage. The star would need to be very hot and not highly luminous, and the dust abundance should be very low, to avoid reradiating too much of the stellar light in the infrared and be consistent with the upper limit on the K band flux (K band absolute magnitude above 1) and the observed flux at longer wavelengths (Gillessen et al. 2012). This model also has severe problems: in order to be hot enough and faint enough, the star should be smaller than a solar radius, and any wind would then be too fast to produce the observed cloud over the period of the orbit of 130 years. Furthermore, with no more than  $\sim 10^4$  low-mass stars expected within 0.04 pc from the Galactic center, it is very unlikely to catch one just at a very brief and rare stage of its stellar evolution while no other luminous old giant in a stage of longer duration has been found so close to the center.

A third possibility is that the cloud is formed by photoevaporation of a circumstellar disk around a star that should be embedded in the cloud (Murray-Clay & Loeb 2012). The circumstellar disk may have formed as usual by gas accretion when the star was formed in the recent starburst. As long as the star is not very massive its K-band flux is far below the observational upper limit (Gillissen et al. 2012). At an initial orbital radius of 8000 AU for the star, the disk would be tidally limited to a size of  $\sim 10$  AU. Murray-Clay & Loeb (2012) proposed that this disk produces the observed cloud of 100 AU after the star is deflected and falls for the first time to a small peribothron, leading to faster photoevaporation and tidal stretching. The problem with this model is the difficulty in deflecting the star from an orbit with small eccentricity in the disk of young stars to the observed highly eccentric orbit without disrupting the gaseous disk.

This is easily seen by considering an encounter with a typical  $M = 10 M_{\odot}$  star (the dynamical relaxation rate is dominated by massive perturbers), moving with a relative velocity  $\sigma \sim 200 \text{ km s}^{-1}$  characteristic of the disk velocity dispersion, at an impact parameter  $b = 10$  AU, where the velocity deflection is  $\Delta v = 2GM/(b\sigma) = 10 \text{ km s}^{-1}$ . The disk circular velocity at 10 AU is similar to  $\Delta v$ , so the disk would already lose a large fraction of its mass for this impact parameter and would be destroyed in closer encounters. On the other hand, deflecting the star from a disk orbit to the observed highly eccentric orbit requires a velocity change  $\Delta v \sim 500 \text{ km s}^{-1}$ , which is clearly impossible to achieve over a single orbit (in fact, the probability for just one such encounter at  $b \sim 10$  AU over one orbit for any given star in the disk is much less than unity).

Nevertheless, the possibility to produce the cloud from a photoevaporating circumstellar disk around a low-mass star is an interesting one, since it can naturally produce many of the observed features of the cloud. It is therefore natural to ask if there are other ways of producing a gas disk around a star in the environment of the Galactic center.

This paper proposes that a disk was formed when an old, low-mass star suffered a close encounter with a stellar black hole, which tidally disrupted its outer envelope and deflected the star into its present orbit. Even though some of the tidal debris may have escaped the star, a large fraction of the mass stayed bound and fell back to the star, creating a small disk. The star was also spun up by the encounter, and may gradually have transferred its angular momentum to the disk, thereby causing an expansion of the disk. The disk then creates a cloud like the one observed at every orbit. Most of the disk mass stays within the tidal radius of 1 AU at the peribothron, while a small fraction migrates out to a larger radius at every orbit, where it is photoionized and drives a wind that generates the cloud.

We shall first discuss the rate at which encounters of stars and stellar black holes that can lead to substantial disruption and disk formation should occur near the Galactic center in §2. The possibility to create the observed cloud from the disk is considered in §3, and we summarize the tests of the model and our conclusions in §4.

## 2. Disrupting encounters of stars with stellar black holes

### 2.1. The density of stars and black holes

The most likely place in the Galaxy where a disrupting encounter between a normal star and a stellar black hole may take place is near the Galactic center, where both the density of stars and black holes are highest. The density of stellar black holes should be particularly enhanced owing to the migration of the most massive objects in the old stellar population of the bulge towards the center. About  $\sim 20000$  stellar black holes were estimated to have migrated to the stellar cusp surrounding Sgr A\* over the age of the Galaxy, which should dominate the mass in the innermost region (Morris 1993; Miralda-Escudé & Gould 2000). A stellar cusp undergoing dynamical relaxation with a constant outflow of orbital energy should have a density profile  $\rho(r) \propto r^{-7/4}$  (Bahcall & Wolf 1976, 1977); the total profile may vary when a range of stellar masses is present, but does not strongly deviate from this form (e.g., ?). The population of old stars dominates the contribution to the stellar mass at large radius, and there is a critical radius  $r_b$  within which the stellar black holes dominate. Inside  $r_b$ , the density of stellar black holes,  $\rho_b$ , probably approaches the 7/4 slope, and their profile becomes much steeper outside  $r_b$ . The density of low-mass stars,  $\rho_s$ , probably approaches a 3/2 slope inside  $r_b$ , corresponding to a constant phase space density in the Keplerian potential, although the profile may be a bit flatter if many stars are destroyed by collisions.

Assuming that the total stellar mass roughly follows the 7/4 slope and normalizing the profile to a total mass  $10^6 M_\odot$  within 1 pc (Genzel et al. 2010), and if a total of 20000 stellar black holes with an average mass of  $M_b = 10 M_\odot$  have migrated to this region, then a mass equal to that of all the stellar black holes is contained within  $r_b \simeq 0.3$  pc. Their number density at  $r < r_b$  is

$$n_b(r) = n_{b0} (r/r_b)^{-7/4} \quad (r < r_b) . \quad (1)$$

We use the normalization  $n_{b0} = (5/16\pi) 5 \times 10^3 r_b^{-3}$ , which assumes that 25% of the stellar black holes are inside  $r_b$ , while the other 75% are outside following a steeper profile. The remaining 75% of the mass inside  $r_b$  is treated here for simplicity as a single population of main-sequence stars with mass  $M_s = 1 M_\odot$ , with a profile

$$n_s = 36 n_{b0} (r/r_b)^{-3/2} \quad (r < r_b) . \quad (2)$$

This simple model yields mass densities similar to those found in the Fokker-Planck calculation of Hopman & Alexander (2006).

### 2.2. Impact parameters

In order to create a disk, an encounter needs to be close enough to cause a strong tidal distortion and raise matter into orbit around the star. We consider a star of mass  $M_s$  and radius

$r_s$  encountering a stellar black hole of mass  $M_b$  at an initial relative velocity  $v_r$ , with an impact parameter  $b$  leading to a closest approach at peribothron at a distance  $r_p$ . The velocity of the star at peribothron, approximating the trajectory of its center of mass to be the same as for a point particle, is  $v_p = (v_r^2 + 2GM_b/r_p)^{1/2}$ , and conservation of angular momentum implies  $r_p = bv_r/v_p$ . We first consider the case  $v_r < v_0$ , where we define

$$v_0 \equiv v_e \left( \frac{M_b}{\sqrt{2}M_s} \right)^{\frac{1}{3}} = \left[ \frac{G(2M_b)^{2/3} M_s^{1/3}}{r_s} \right]^{\frac{1}{2}}, \quad (3)$$

and  $v_e = (2GM_s/r_s)^{1/2}$  is the escape velocity of the star. For this case, we use the strong disruption condition that the tidal acceleration caused by the black hole between the center and surface of the star along the radial line at peribothron, at distances  $r_p$  and  $r_p - r_s$ , is equal to the gravitational acceleration on the surface due to the star. This implies  $2M_b r_s / r_p^3 = M_s / r_s^2$ , or a maximum peribothron distance for tidal disruption of

$$r_p = r_s \left( \frac{2M_b}{M_s} \right)^{\frac{1}{3}} \quad (v_r < v_0). \quad (4)$$

This condition agrees with the maximum impact parameter found in numerical simulations required for stripping matter (e.g., Khokhlov et al. 1993; note that the approximation used in these simulations that  $r_p \gg r_s$  is only marginally correct for our case). The condition  $v_r < v_0$  ensures that the velocity at peribothron is  $v_p \simeq (2GM_b/r_p)^{1/2} = v_0$ , and the duration of the strong tide is  $t \simeq r_p/v_p = \sqrt{2}r_s/v_e$ , equal to the free-fall time of the star. For the case  $v_r > v_0$ , gravitational focusing remains small at  $r_p$ , and so  $v_p \simeq v_r$  and the duration of the strong tide is shorter than the star free-fall time by the factor  $v_r/v_0$ . Our condition for strong distortion is in this case  $2M_b r_s / r_p^3 (r_p/v_r) = M_s / r_s^2 (\sqrt{2}r_s/v_e)$ , or

$$r_p = r_s \left( \frac{2M_b}{M_s} \right)^{\frac{1}{3}} \left( \frac{v_0}{v_r} \right)^{\frac{1}{2}} \quad (v_r > v_0). \quad (5)$$

The corresponding maximum impact parameters are

$$b = r_p \frac{v_p}{v_r} \simeq r_s \left( \frac{2M_b}{M_s} \right)^{\frac{1}{3}} \frac{v_0}{v_r} \quad (v_r < v_0), \quad (6)$$

$$b \simeq r_p \simeq r_s \left( \frac{2M_b}{M_s} \right)^{\frac{1}{3}} \left( \frac{v_0}{v_r} \right)^{\frac{1}{2}} \quad (v_r > v_0). \quad (7)$$

We do not take into account a minimum impact parameter, even though the star is totally disrupted when the impact parameter is sufficiently small. The impact parameter required for a complete destruction should be substantially smaller than the maximum values. The large degree of concentration of stars implies that the dense core is hard to disrupt and can have a disk forming around it even when a large fraction of the star is tidally pulled out.

For much larger velocities,  $v_r > v_e(M_b/M_s)$ , strong disruption requires the black hole to cross through the star and becomes inefficient as the tidal acceleration acts over a shorter time. Some material may be dragged out of the star through the narrow cylinder that the black hole should perforate, but it would be difficult for any disk to be formed.

### 2.3. The rate of disrupting encounters

The rate of encounters at impact parameters smaller than the maximum values for disruption in equations (6) and (7) can now be calculated as

$$R = 4\pi^2 \int dr r^2 n_b(r) n_s(r) \langle b^2 v_r \rangle , \quad (8)$$

where  $v_r$  is the relative velocity between a star and a black hole, and  $\langle b^2 v_r \rangle$  is computed by averaging over the velocity distributions at a given radius.

Dynamical equilibrium implies that the rms velocity dispersion of a set of particles moving in a Keplerian potential with a density profile  $n \propto r^{-\gamma}$  is  $\sigma^2 = GM/r/(\gamma+1)$ . Hence, the rms relative velocity of stars and stellar black holes at a distance  $r$  from the central black hole of the Milky Way of mass  $M$  (referred to as Sgr A\*) is

$$\langle v_r^2 \rangle = \frac{3GM}{r} \left( \frac{2}{5} + \frac{4}{11} \right) = \frac{126}{55} \frac{GM}{r} . \quad (9)$$

There is a critical radius  $r_0$  at which this rms relative velocity is equal to  $v_0$ ,

$$r_0 = r_s \frac{63}{55} \frac{M}{M_s} \left( \frac{\sqrt{2}M_s}{M_b} \right)^{\frac{2}{3}} \simeq 6000 \text{ AU} . \quad (10)$$

We also define the radius at which the rms relative velocity reaches  $v_e M_b/M_s$ , within which disruptions become inefficient,

$$r_f = r_s \frac{63}{55} \frac{M}{M_s} \left( \frac{M_s}{M_b} \right)^2 \simeq 200 \text{ AU} . \quad (11)$$

Approximating also  $\langle 1/v_r \rangle \simeq (\langle v_r^2 \rangle)^{-1/2}$ , the total rate of encounters from equation (8) is

$$R = 4\pi^2 r_b^3 36 n_{b0}^2 r_s^2 v_e \frac{\sqrt{2}M_b}{M_s} \times \left[ \int_{r_f/r_b}^{r_0/r_b} dx x^{-\frac{5}{4}} + \left( \frac{r_0}{r_b} \right)^{-\frac{1}{2}} \int_{r_0/r_b}^1 dx x^{-\frac{3}{4}} \right] . \quad (12)$$

The first integral arises from the outer region  $r > r_0$ , where slow encounters affected by gravitational focusing dominate, and the second integral is for  $r < r_0$ , where fast encounters limited by the duration of the strongest tidal acceleration dominate. The result is,

$$R = 576\pi^2 r_b^3 n_{b0}^2 r_s^2 v_e \frac{\sqrt{2}M_b}{M_s} \times \left[ \left( \frac{r_b}{r_f} \right)^{\frac{1}{4}} + \left( \frac{r_b}{r_0} \right)^{\frac{1}{2}} - 2 \left( \frac{r_b}{r_0} \right)^{\frac{1}{4}} \right] \simeq 10^{-6} \text{ yr}^{-1} . \quad (13)$$

The rate of interesting encounters in radial shells of constant logarithmic width is fairly flat, but it is actually maximum at the smallest radius, near  $r_f$ . If the observed cloud is indeed being produced by a distorted star, it is interesting to note that even though the encounter could have occurred at any point along its orbit, the most likely place would be near the peribothron, which is close to  $r_f$ . In this case, the black hole would have rushed very close to the surface of the star at  $\sim 6000 \text{ km s}^{-1}$ .

The predicted rate of encounters implies that the “shaken” star needs to produce the observed cloud for many orbits in order that we have a reasonable probability to be observing the cloud at a random time.

## 2.4. Effects of other types of collisions

A small disk around a star may also be formed as a result of the collision between two main-sequence stars. In this case, a strong tidal disruption requires a physical collision, and encounters at radius smaller than 0.1 pc would typically occur at relative velocities greater than the escape velocity. The process of disk formation becomes inefficient at these large velocities because most of the debris that are generated should end up on unbound orbits. Therefore, while collisions between stars may form similar disks at even higher rates than black hole flibies, most of them would be produced on orbits with much larger apobothrons than the observed cloud.

## 3. Evolution of the stellar disk and wind

After a strongly distorting encounter, the debris lifted from the star may either become unbound or fall back to the star. A large fraction of the stellar mass might be lost (10-50%), and the star that remains may be strongly spun up (see ?). It is reasonable that  $\sim 1$  to 10% of the stellar mass may form a disk around the star, extending to no more than a few stellar radii because most of the debris should not acquire a large specific angular momentum. After the encounter, the star may settle to an equilibrium with an equatorial radius larger than its main-sequence value because of fast rotation and the dissipation of energy into internal heat, which will take a Kelvin-Helmholtz time ( $\sim 10^7$  years) to be radiated away.

### 3.1. Required wind speed

In order to make the observed gas cloud, the star and disk need to generate a wind with an adequate mass loss rate to deliver the mass of the cloud over an orbital period, and at a velocity that is low enough not to exceed the observed present size of 100 AU. We can approximately treat the motion of a gas element in the wind moving away from the star, by approximating the falling trajectory of the star from its apobothron to its peribothron as if it were on a purely radial orbit

with zero orbital energy (the actual observed cloud is on an orbit with eccentricity  $e = 0.94$ ). The distance  $r$  from the star to Sgr A\* at time  $t$  is then

$$r(t) = \left[ \frac{3}{2} \sqrt{2GM} (t_0 - t) \right]^{\frac{2}{3}}, \quad (14)$$

where  $t_0$  is the time when the star would reach  $r = 0$  if it were in a purely radial orbit. A gas element separating along the radial direction at a distance from the star  $x(t) \ll r$  is affected by a tidal acceleration  $g_t = 2GMx/r^3$ . Neglecting the gravity of the star (which is only important at an initial time when the wind is launched from a small value of  $x$ ) and any ram-pressure force due to the hot medium around Sgr A\* (see Gillessen et al. 2012 and Burkert et al. 2012 for a discussion of the effects of ram-pressure), the motion for the gas element is described by the equation

$$\frac{d^2x}{dt^2} = \frac{2GMx}{r^3} = \frac{4x}{9(t_0 - t)^2}. \quad (15)$$

Assuming that the gas element is at a distance equal to the observed cloud size,  $x_1 \simeq 100$  AU, at the time  $t_1 \simeq t_0 - 2$  yr of the observations reported by Gillessen et al. (2012), and that it was emitted by the wind from a distance  $x \ll x_1$  near the time of the apocenter,  $t_a \simeq t_0 - 70$  yr, the solution to the above equation is (using  $t_0 - t_a \gg t_0 - t_1$ ),

$$x(t) = x_1 \left( \frac{t_0 - t_1}{t_0 - t} \right)^{\frac{1}{3}} \left[ 1 - \left( \frac{t_0 - t}{t_0 - t_a} \right)^{\frac{5}{3}} \right]. \quad (16)$$

The initial velocity of the wind therefore should be about

$$\dot{x}(t_a) = \frac{5x_1(t_0 - t_1)^{1/3}}{3(t_0 - t_a)^{4/3}} \simeq 4 \text{ km s}^{-1}. \quad (17)$$

If the disk formed after the tidal encounter of the star with a black hole is no bigger than a few stellar radii, any wind that is generated from the disk using energy from the stellar rotation or the accretion of disk material to the star would have a velocity of hundreds of  $\text{km s}^{-1}$ , much too fast to explain the observed cloud. To generate the required slow wind, a mechanism needs to be present to expand the disk and to provide energy for launching a wind from large radius.

### 3.2. Disk expansion

A mechanism for this disk expansion may be the fast rotation of the perturbed star. Note that the star may already have been a fast rotator before the encounter that created the disk, because previous encounters with stellar black holes in the Galactic center region at larger impact parameters (which occur more frequently) may have gradually spun up the star (?); the last, closest encounter may simply have cracked up the rotation rate even further. After the encounter, a process of angular momentum exchange from the star to the disk should result in an expansion of the disk.



If the star rotates very fast, it may become prolate and cause a rotating gravitational tide on the inner disk that can transfer the angular momentum. An oblate star that is still rotating faster than the inner disk can continue to transfer angular momentum if it is magnetically connected to the disk. The disk will be spread by internal transport of angular momentum, pushing matter on the outer edge to an increasing orbital size as more angular momentum is acquired from the star on the inner edge.

Let the angular momentum of the star after it has settled to hydrostatic equilibrium following the encounter with the black hole be  $L_s = \phi_L \sqrt{GM_s^3 r_s}$ . As an example, for a spherical object with a singular isothermal density profile truncated at  $r_s$ , and a surface rotation velocity equal to the circular orbital velocity,  $\phi_L = 2/9$ . The angular momentum is even larger for a prolate star rotating near the maximum rate which has expanded owing to the increase of internal energy (decrease in absolute value) in the tidal event. The angular momentum of the disk of mass  $M_d$  is  $L_d = M_d \sqrt{GM_s r_d}$ , where  $r_d$  is the characteristic disk radius obtained from its mass-weighted average of  $\sqrt{r}$ . If the star transfers most of its angular momentum to the disk, the final radius of the disk is

$$r_d = r_s \left( \frac{\phi_L M_s}{M_d} \right)^2. \quad (18)$$

For  $M_d = 0.1 \phi_L M_s$ , the disk can expand out to  $100 r_s$ , or 0.5 AU for a solar-type star.

If, as proposed in this paper, this star and expanded disk system are inside the observed cloud in the Galactic center, the disk cannot expand beyond  $r_d \sim 0.5$  AU because the tidal limit at the peribothron of the cloud orbit,  $r_{cp}$ , is  $r_t = r_{cp} [M_s/(2M)]^{1/3} \simeq 0.7$  AU, so the disk is truncated at this size at every orbital period of 130 years.

### 3.3. Mass loss rate

The escape velocity from the surface of a disk at  $r_d \sim 0.5$  AU is  $\sim 60 \text{ km s}^{-1}$ , still too large to generate a slow wind at a velocity of a few  $\text{km s}^{-1}$ . An additional mechanism is required to first spread a small fraction of the gas in the disk over a larger region around the star at every orbit, which can then be blown out at a low velocity. Moreover, photoionization from the massive stars near the Galactic center can provide the energy required to generate the wind once some material expands to the radius where the escape velocity is reduced to near the isothermal sound speed at the temperature of photoionized gas,  $c_i \simeq 11(T/10^4 \text{ K})^{1/2} \text{ km s}^{-1}$  (Murray-Clay & Loeb 2012). As the wind escapes the gravity of the star, its velocity can be moderately reduced below  $c_i$  to the value required to reproduce the size of the observed cloud.

The total mass loss rate from a cloud of radius  $r_c$  that is being photoevaporated by an external flux of ionizing photons  $F_i$  can be roughly estimated as  $\dot{M} \sim 4\pi r_c^2 c_i n_e \mu_e$ , where  $n_e$  is the electron density in the external ionized layer that shields the interior of the cloud, and  $\mu_e$  is the mean mass per electron. The condition that the ionizing flux is balanced by a recombination rate column

$\alpha_B n_e^2 \ell$ , where  $\alpha_B$  is the case B recombination coefficient and  $\ell \sim r_c$  is the length of the ionized layer, is then used to estimate  $n_e \sim [F_i/(\alpha_B r_c)]^{1/2}$ . A detailed calculation was presented by Bertoldi & McKee (1990), who obtained

$$\dot{M} = 1.4 \times 10^{-11} \phi_w \frac{S_{49}^{1/2}}{d_{pc}} r_{\text{AU}}^{3/2} M_{\odot} \text{ yr}^{-1}, \quad (19)$$

where  $r_{\text{AU}} = r_c/(1 \text{ AU})$  is the radius of the photoevaporating cloud expressed in AU,  $\phi_w$  is a dimensionless factor that is written as a combination of other modeling dimensionless factors in equation (4.2) of Bertoldi & McKee (1990), and the external flux is expressed as  $F_i = 10^{49}/(4\pi) S_{49}/d_{pc}^2 \text{ pc}^{-2}$ , with  $S_{49}$  equal to the total emission rate of ionizing photons in units of  $10^{49} \text{ s}^{-1}$  from a source at a distance  $d_{pc}$  expressed in parsecs. Here, we assume that the stars in the young disk emit  $S_{49} = 10$  (which is 15% of all the ionizing luminosity in the central 0.5 pc; see Genzel et al. 2010) from a typical distance of 0.06 pc, which yields  $S_{49}^{1/2}/d_{pc} = 50$ , or  $F_i = 2 \times 10^{14} \text{ cm}^{-2}$ . The parameter  $\phi_w$  depends on a photoevaporation parameter defined as  $\psi = \alpha_B F_i r_c / c_i^2$ . Using  $c_i = 11 \text{ km s}^{-1}$  (at  $T = 10^4 \text{ K}$ ) and  $r_c = 5 \text{ AU}$ , we find  $\psi \simeq 3000$ . The value of the dimensionless factor is then  $\phi_w \simeq 4$ , as shown in Figure 11 of (Bertoldi & McKee 1990), and the inferred mass-loss rate is  $\dot{M} \simeq 3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$  for a cloud size of  $r_{\text{AU}} = 5$ .

Therefore, as long as a mass of at least  $3 \times 10^{-6} M_{\odot}$  can be expelled from the disk after the star has passed by the peribothron, and can reach out to a distance from the star  $r_c \sim 5 \text{ AU}$ , then this mass can be slowly lost from the system over an orbital period of  $\sim 100$  years, roughly at the desired wind speed to produce the observed cloud. This amount of mass in a region of a radius  $r_c = 5 \text{ AU}$  has a number density  $n \sim 10^9 \text{ cm}^{-3}$ , which is self-shielded behind an ionized layer with  $n_e \simeq 10^{6.5} \text{ cm}^{-3}$ .

How can this mass move from the disk out to  $\sim 5 \text{ AU}$  and stay there for  $\sim 100$  years? A possible way for this to happen is discussed next.

### 3.4. Generation of photoevaporating cloud from the disk

As described previously, the disk around the star can transport a mass up to  $\sim 0.03 M_s$  to a radius  $\sim 0.5 \text{ AU}$ . Therefore, a fraction of only  $10^{-4}$  of the disk mass needs to be ejected out to a large distance to generate a photoevaporation rate of  $3 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$  over 100 years. If a mechanism to eject this small fraction of the disk mass near the escape velocity exists, this can in principle occur at every orbit after the peribothron passage and create a similar cloud to the one we observe for up to  $10^4$  orbits, or a total time of  $10^6$  years. The rate of encounters between stars and black holes in equation (13) would then imply that on average, one cloud like the one observed is present at any time near the Galactic center. This requires the disk to expand and eject mass at every orbit in an optimal way, but even if the process is much less optimal, the probability to observe the cloud at a random time can still be a reasonable one.

We note that the inferred mass of the observed cloud is  $M_c \simeq 10^{-5} f_V^{1/2} M_\odot$ , where  $f_V$  is the filling factor of gas with density  $n_e \simeq 10^{5.5} f_V^{-1/2}$  in a spherical cloud with radius  $\sim 100$  AU (Gillessen et al. 2012). A filling factor  $f_V \sim 0.1$  is probably most reasonable, because the cloud is expected to have a filamentary shape owing to the tidal acceleration that stretches the cloud in the direction of the orbit and compresses it across both perpendicular directions. Only the long axis of the cloud is observationally resolved.

The mechanism to eject a small fraction of the mass may occur when the disk undergoes rapid precession and is strongly warped in its outer part when the star reaches its peribothron. If the disk expands slowly as the star loses angular momentum, a very small fraction of the disk may diffuse outside the tidal radius during one orbit, but a larger fraction may be present into the intermediate region near 0.5 AU where the disk is not yet torn apart but is substantially warped and perturbed, leading to collisions of gas streams and shocks that can eject gas near the escape velocity. Inevitably, some of the ejected mass will escape the system, but some may simply move out on a large orbit and remain bound to the star. Material that is ejected near the escape velocity from the disk just after the peribothron passage can remain near a separation from the star where the tidal acceleration from Sgr A\* is comparable to the gravitational attraction of the star. Complex orbits are therefore possible that leave gas streams far from the disk with enough angular momentum to prevent them from falling back to the disk. Furthermore, as the gas moves out it will be photoionized, and even the gas that remains shelf-shielded is heated by the ambient ultraviolet light below the ionization threshold, keeping it at a temperature above 1000 K. Because the outflow from the disk is non-spherical and highly inhomogeneous, pressure gradients can change the velocity of gas streams by  $\sim 3 \text{ km s}^{-1}$ , again providing substantial angular momentum.

The scenario that this leads to is of a large region of turbulent gas motions around the smaller disk, with random gas streams moving on different orbits. Eventually these gas streams would collide and cool, and if the net angular momentum of the gas is still small, most of the gas should fall back to the disk. However, it may take several orbits for this process to be completed, and gas streams at  $\sim 5$  to  $10$  AU from the star need only survive for a few orbits to produce a steady wind until the next peribothron passage. In practice, a larger amount of mass may probably come off the disk at every peribothron, but the largest fraction of this may be launched on small orbits where it should indeed homogenize, cool and fall back to the central disk, while a smaller amount of gas that moves out on larger orbits may suffice to sustain the photoevaporation wind.

#### 4. Summary and Conclusions

A model is proposed in this paper to explain the origin of the gas cloud described by Gillessen et al. (2012). At some point along the present orbit of the gas cloud, a close encounter of a star and a stellar black hole occurred perhaps  $10^4$  or  $10^5$  years ago that strongly disrupted the star, tearing out a substantial fraction of its mass into debris and spinning up the star to near the break-up

point. The fraction of the debris that remained bound to the star either fell back on the star or formed a small disk around it. The star, placed on the orbit of the observed cloud, settled back to equilibrium with fast rotation, perhaps with a prolate shape initially. Subsequently, the disk gradually expanded as it absorbed the angular momentum of the star, until its outer edge reached the truncation radius at peribothron. After this time, the disk has been launching a fraction of its mass at every peribothron passage in gas streams that arise from the strong tidal perturbation on the outer disk edge. Most of the streams remain on small orbits and fall back to the disk shortly afterwards, but a small fraction are launched out to 5 to 10 AU where there is not enough time for them to collide, cool and fall back to the disk. The photoevaporation of these streams by the ambient ionizing radiation generates a wind, which is elongated into a filament by the tidal force as the star falls back to the peribothron on its next orbit and produces a cloud like the observed one.

The material that reaches the outer edge of the disk at  $\sim 0.5$  AU over the entire duration of the cloud-generating phenomenon may be as much as  $0.03 M_{\odot}$  for a rapidly rotating star. Several inefficiency factors are likely to be present to convert this mass into the photoionized clouds that are produced at every orbit: some mass can escape the system directly after being ejected from the disk, and not all the photoionized wind may follow the star in a single coherent cloud for the whole orbit if hydrodynamic instabilities induced by ram-pressure from the hot medium can fragment the cloud. Even if these inefficiency factors are large or the mass that can reach the disk outer edge is smaller, the probability to see the cloud can still be reasonable. For example, if the cloud were generated for only 100 orbits, requiring a total mass of just  $\sim 10^{-3} M_{\odot}$  to be placed on the photoevaporating gas streams over all the orbits, then the rate obtained in equation (13) implies a probability of 1% to see this cloud at any random time. This would still be reasonable, taking into account that the probability is calculated a posteriori, after having observed a curious phenomenon in the Galactic center that might be one among many unlikely phenomena that could be observed but are not actually happening at our present time.

The model proposed here can be tested after the cloud passes the peribothron. While the present cloud should be totally disrupted whether or not a star is contained inside it, the star and disk system should follow their unaltered orbit and produce a new cloud. This new cloud will initially be small and will therefore collect much less ionizing radiation for conversion into recombination lines, so it may initially be faint compared to the remains of the present cloud. However, internal shocks in the disk and the ejected gas streams during the peribothron passage may produce a detectable  $\text{Br}\gamma$  intensity that remains unresolved on the predicted Keplerian orbit. Moreover, the tidal perturbation of the disk may result in an increased infrared luminosity. For example, if a mass of  $10^{-3} M_{\odot}$  is present near the outer edge of the disk and is shocked at velocities of  $\sim 30 \text{ km s}^{-1}$ , the energy released can be up to  $10^{43}$  ergs and the disk may radiate up to  $100 L_{\odot}$  during several months after the peribothron passage with a surface temperature near 2000 K, making it detectable in the K band. Subsequently, the unresolved cloud may be hard to detect for the first few years because of its small area and the fact that most of the gas in streams may remain

self-shielded. Eventually, the cloud should gradually grow and increase its line luminosity as more gas is exposed to the external radiation. The rate of increase of the line luminosity depends on the amount of gas that escapes from the system after the peribothron and its velocity. If the model presented here is correct, the process of mass ejection from the disk will be characterized by the recombination line lightcurve observed from the unresolved source and its size and shape after it can be resolved again.

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